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ANALYSIS OF JUNCTION TRANSISTOR CONVERTERS

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ANALYSIS OF JUNCTION TRANSISTOR CONVERTERS

/Following is a translation of an article by Ch'eng Chung-chih in the Chinese-languate periodical Wu-li Hsueh-pao (Acta Physica Sinica), Peiping, Vol. XV, No. 10, October 1959, pages 525-533./

"This paper describes a detailed analysis of conversion properties of junction transistors. A new parameter "the effective conversion transconductance" is introduced for characterizing transistor converters. The effective conversion trrnsconductance of transistors converters using a PNP transistor operated at different oscillatory conditions and at various signal frequencies are studied. Main differences between transistor converters and vacuum tube converters are compared."

1. Introduction

Transistors have already been widely used in superheterodyne type receivers, and have been effectively used as converters. However, one finds in the information available that a good theory for transistor converters is lacking. This paper analyzes the application of the junction transistor converter, and introduces a new parameter "the effective conversion transconductance" to determine the characteristics of a converter. We calculated this parameter and its difference with the conversion transconductance used in vacuum-tube converters. We also found the relationship between this parameter and the oscillatory conditions, as well as the relationship between this parameter and the characteristic of the transistor. A sample calculation is given for the case of a PNP junction type transistor manufactured by the alloy process. This method of analysis can also be applied to other higher-frequency type transistor converters.

There exists a /1-3/ considerable amount of theoretical analysis of vacuum-tube and diode converters. The method of analysis used there can also be applied to analyze transistor converters.

However, due to the difference of the basic characteristics of the vacuum tube and transistor, the conditions of application of the vacuum tube converter and the transistor converter are also different. This article points out the important difference between these two kinds of converters.

The basic circuits of a transistor are common-base, common-emitter and common-collector; the common-emitter circuit is best for high efficiency. This paper shall use the common-emitter circuit for discussion. The practical example uses a PNP junction transistor manufactured by the alloy process.

Figure 1 [see Figure Appendix] shows the block diagram of a common-emitter converter. The input signal $v_s(t)$ and oscillatory signal $v_o(t)$ are fed in between the base B and the returning path of the emitter E; the intermediate frequency signal $i_{i.f.}(t)$ is obtained between the collector C and the returning path of the emitter E. We have

$$v_o(t) = u + V_o\cos(w_o t) \tag{1}$$

$$v_s(t) = V_s\cos(w_s t - \phi_s). \tag{2}$$

u in equation (1) represents the bias between base and emitter under oscillatory condition. Vo is the amplitude of the oscillatory signal, wo is the angular frequency of the oscillatory signal. V_s in equation (2) is the amplitude of the input signal; ϕ_s is the phase angle and w_s is the input angular frequency, with

$$w_o - w_s = w_{i.f.} \quad ,$$

$w_{i.f.}$ in the above equation is the intermediate angular frequency. In the following analysis, we shall neglect the effect of signal frequency w_i ($w_i = w_o + w_{i.f.} = w_s + 2\, w_{i.f.}$) and the harmonics ($nw_o$; $n = 2,3 \ldots$) of the oscillatory signal on conversion. If during the application of conversion, the amplitude of the input signal is smaller than the oscillatory amplitude ($V_s \ll V_o$), the DC application condition of the transistor convertor changes periodically according to the oscillatory signal.

The transistor circuit can be represented by various small-signal equivalent circuits. This article uses one of them and it is shown on Figure 2[4]. The parameters ($r_{bb'}, g_{b'e}, c_{b'e}, g_{b'c}, c_{b'c}, g_{ce}, g_m$) of the equivalent circuit are determined under DC tests of the transistor.

The DC condition of the transistor converter changes according to the oscillatory signal, hence these parameters also change in time according to the oscillatory signal. They become functions of time and are represented by $r_{bb'}(t), g_{b'e}(t), c_{b'e}(t), g_{b'c}(t), c_{b'c}(t), g_{ce}(t), g_m(t)$. Figure 2 with these time-dependent parameters shows the use of the converter. Point B represents the base, E the emitter, C the collector and B' is some point of the base. B',C,E three points forms the basic circuit of the transistor and B,C,E, three points form the actual transistor. $r_{bb'}$ represents the base resistance. The signal at the output point of the current generator $g_m V_{b'e}$ is proportional to that between B' and E. This important point distinguishes the actions of the transistor converter and the vacuum-tube converter. The input point of Figure 2 has connected in series an internal impedance Z_s with a signal generator of amplitude V_s and an internal impedance Z_o with an oscillator of amplitude V_o. The output end is connected with the load Z_e.

2. Conversion Transconductance "g_{ci}"

The transconductance of a transistor can be obtained from the slope of the static curve (the relation between V_{BE} and I_C when V_c is fixed):

$$g_m = \left.\frac{\partial I_c}{\partial V_{BE}}\right|_{V_c} \tag{3}$$

Figure 3 shows a static curve of a typical medium-frequency PNP germanium transistor. The figure also shows a group of small-signal parameters when $V_c = -6$ v., $I_c = -1$ amp. From Figure 3 one uses graphic method to find transconductance at each point and also the relation between transconductance and bias voltage. It is shown in Figure 4. During application as a converter, the transconductance changes according to the oscillatory action,

$$g_m(t) = \sum_{n=0}^{\infty} a_n \cos n w_o t \tag{4}$$

Suppose the output current is,

$$i(t) = g_m(t) v_s(t) \tag{5}$$

Substitute (2), (4) into (5), and we obtain

$$i(t) = \sum_{n=0}^{\infty} a_n \cos n w_o t \, v_s \cos (w_s t - \varphi_o) =$$

$$\frac{a_1}{2} v_s \cos [(w_o - w_s) t + \varphi_o] + \dots \tag{6}$$

From the first term of (6), we obtain the intermediate-frequency current

$$i_{i.f.} = \frac{a_1}{2} V_s \cos (w_{i.f.} t + \varphi_o) = g_{c1} V_s \cos (w_{i.f.} t + \varphi_o = I_{i.f.} \cos (w_{i.f.} t + \varphi_o) \tag{7}$$

In (7) g_{c1} is called the "conversion transconductance" with,

$$g_{c1} = \frac{\partial I_{i.f.}}{\partial V_s} = \frac{a_1}{2} \tag{8}$$

One can use different methods to obtain the value of g_{c1}. The usual method is the 7-point graphic method [1]. From Figure 5, we obtain

$$g_{c1} = \frac{1}{12} [(g_7 - g_1) + (g_5 - g_3) + 1.73 (g_6 - g_2)] \tag{9}$$

The meaning of $g_1 g_2 \dots g_7$ can be seen from Figure 5 and reference [1].

The above method (eq. (5) to (9)) for obtaining the "conversion transconductance" is the same as for the vacuum-tube converter. "Conversion transconductance" is used in representing the conversion ability of vacuum-tube converters. One usually bases on this parameter in selecting vacuum-tube converters. However one cannot use g_{c1} alone in determining the conversion ability of a transistor converter, because for transistor converters the assumptions of equation (5) are not satisfied. The output current is related to $V_{b'e}(t)$

$$i(t) = g_m(t) v_{b'e}(t). \tag{10}$$

Hence we must look for a new parameter to characterize the conversion ability of a transistor converter. As a result of research, we obtain a new parameter called "effective conversion transconductance" represented by $g_{\xi 1}$.

e. "Effective Conversion Transconductance" $g_{\xi 1}$

Change (10) to

$$i(t) = g_m(t) v_{b'e}(t) \frac{v_{be}(t)}{v_{be}(t)} \quad \frac{v_s(t)}{v_s(t)} = g_m(t) \left[\frac{v_{b'e}(t)}{v_{be}(t)} \right] \left[\frac{v_{be}(t)}{v_s(t)} \right] v_s(t) \tag{11}$$

Substitute (2), (4) into (11) and obtain the intermediate-frequency current as,

$$i_{i.f} = \left[\frac{a_1}{2} \quad \frac{V_{b'e}}{V_{be}} (w_s) \quad \frac{V_{be}}{V_s} (w_s) \right] \quad V_s \cos (w_{i\,f.} t - \varphi_o). \tag{12}$$

From (12), we obtain the relation between the output intermediate-frequency current and the input signal,

$$\frac{\partial I_{i.f.}}{\partial V_s} = \left[\frac{a_1}{2} \quad \frac{V_{b'e}}{V_{be}} \quad (w_s) \; \frac{V_{be}}{V_s} \; (w_s) \right] = \left[g_{c1} \frac{V_{b'e}}{V_{be}} \quad (w_s) \; \frac{V_{be}}{V_s} \; (w_s) \right] \tag{13}$$

Let the input impedance of the converter be $Z_{in}(w_s)$ and the oscillatory generator impedance $Z_o(w_s) \longrightarrow o$ then,

$$\frac{V_{be}(w_s)}{V_s(w_s)} = \frac{1}{1 + \frac{Z_s}{Z_{in}} \quad (w_s)} \tag{14}$$

Equation (14) shows $\frac{V_{be}(w_s)}{V_s(w_s)}$ is related to the input signal impedance and the input impedance. In finding a parameter characterizing the ability of the converter, this parameter must be related to the property of the converter, but not the property of the signal generator. Hence let

$$\frac{Z_s \; (w_s)}{Z_{in}(w_s)} \ll 1 \qquad \text{then} \quad \frac{V_{se}}{V_s} \; (w_s) \cong 1$$

Simplify (13)

$$\frac{\partial I_{i.f.}}{\partial V_s} = g_{c1} \; \frac{V_{b'e}}{V_{be}} \; (w_s) \cong g_{\xi 1} \tag{15}$$

From (15), we obtain $g_{\xi 1}$ called "effective conversion transconductance We use it to represent the conversion ability of a transistor and the relationship between the intermediate-frequency signal and the input signal.

4 The Calculation of $\frac{V_{b'e}}{V_{be}}$ (w_s)

"Effective conversion transconductant" g_n is the product of "conversion transconductance" g_{c1} and $\frac{V_{b'e}}{V_{be}}$ (w_s). g_{c1} can be obtained from eq. (9), and the calculation of $\frac{V_{b'e}}{V_{be}}$ (w_s) is described in detail as follows: When the intermediate-frequency load $Z_L(w_{i.f.})$ and the output impedance $Z_o(w_{i.f.})$ of the converter matches $[Z_L(w_{i.f.}) = Z_o^*(w_{i.f.})]$, the condition for maximum efficiency output is met. When operated under conditions of narrow frequency band, the load impedance can be adjusted to very small values for the oscillatory and input signal frequencies $Z_L(w_s) \to o$, $Z_L(w_o) \to 0$. Under this operating condition, the input impedance $Z_{in}(w_s)$ of the converter can be represented by the short-circuit input impedance [Figure 6(a)], wherein $r_{bb'}(t), g_{b'c}(t), g_{b'e}(t), c_{b'c}(t), c_{b'e}(t)$ are time-dependent functions changing according to the oscillatory conditions. The effect of these parameters on the input signal can be approximately represented by their average values in an oscillatory period $(\overline{r_{bb'}}, \overline{g_{b'e}}, \overline{g_{b'c}}, \overline{c_{b'e}}, \overline{c_{b'c}})$.

From the characteristics of a transistor, one obtains, [4]

$$\overline{r_{bb'}(t)} = \overline{r_{bb'}} = r_{bb'}, \tag{16}$$

$$\overline{g_{b'e}} \gg \overline{g_{b'c}}, \tag{17}$$

$$\overline{c_{b'e}} \gg \overline{c_{b'c}}, \tag{18}$$

$$g_{b'e} \cong \frac{q}{KT} I_B \cong - \frac{q}{KT\alpha_{cbo}} I_c, \tag{19}$$

$$c_{b'e} \cong \frac{q}{KT} \frac{W^2}{2D} I_E \cong -\frac{q}{KT}\frac{W^2}{2D}\left(\frac{\alpha_{cbo}}{1+\alpha_{cbo}}\right) I_c, \tag{20}$$

where q is the charge of electron; K is the Boltzmann constant; T is the absolute temperature; W is the base width; D is the dispersion constant; and α_{cbo} is the amplification factor of the common-emitter-short-circuit-low-frequency circuit From (19) and (20) one knows that $g_{b'e}$ and $c_{b'c}$ are proportional to I_c.

Let the values of $g_{b'e}$ and $C_{b'e}$ be g_A and C_A respectively when $I_c = -1$ ma, then

$$g_{b'c} = -g_A I_c, \tag{21}$$

$$c_{b'e} = -c_A I_c, \tag{22}$$

But the average values of $g_{b'e}$ and $c_{b'e}$ during one oscillatory period are

$$\overline{g_{b'e}} = -g_A \overline{I}_c, \tag{23}$$

$$\overline{c_{b'e}} = -c_A \overline{I}_c \tag{24}$$

where $\overline{I}_c$ is the average collector current under oscillatory conditions, and its value can be obtained by the 7- point graphic method as,

$$\overline{I}_c = \frac{1}{12} \left[I_1 + I_7 + 2(I_2 + I_3 + I_4 + I_5 + I_6) \right]. \tag{25}$$

where the meanings of I_1 to I_7 are defined in Figure 5 and reference [1].

From equations (23), (24), (25) and the known values of g_A and C_A, we obtain the values for $\overline{g_{b'e}}$ and $\overline{C_{b'e}}$.

Then from Figure 6(b), we obtain:

$$\frac{V_{b'e}}{V_{be}}(w_s) \cong \frac{1}{1 + r_{bb'}\overline{g_{b'e}} + jw_s r_{bb'}\overline{c_{b'e}}}, \tag{26}$$

The absolute value of $\frac{V_{b'e}}{V_{be}}(w_s)$ is

$$\left|\frac{V_{b'e}}{V_{be}}(w_s)\right| \cong \frac{1}{\sqrt{(1 + r_{bb'}\overline{g_{b'e}})^2 + (r_{bb'}w_s\overline{c_{b'e}})^2}}. \tag{27}$$

If $r_{bb'}\overline{g_{b'e}} \ll 1$, then

$$\left|\frac{V_{b'e}}{V_{be}}(w_s)\right| \cong \frac{1}{\sqrt{1 + (r_{bb'}w_s\overline{c_{b'e}})^2}} = \frac{1}{\sqrt{1 + \left(\frac{1}{Q_s}\right)^2}} \tag{28}$$

where $Q_s = \frac{1}{r_{bb'}w_s\overline{c}_{b'e}}$ represents the Q-value of the R-C circuit formed by $\overline{r}_{bb'}$ and $\overline{c}_{b'e}$ during input.

Substitute eq. (28) into (15), we obtain

$$|g_{\xi 1}| \cong \frac{g_{c1}}{\sqrt{1 + \left(\frac{1}{Q_s}\right)^2}} \cong \frac{g_{c1}}{\sqrt{1 + (r_{bb'}w_s c_{b'e})^2}}. \tag{29}$$

From equation (29), we see the relation between the transistors "effective conversion transconductance" and the static curve, the oscillatory condition and other parameters of the apparatus. It also changes with the input frequency. This property is different from the usual vacuum-tube converter property encountered in broadcast systems.

5. Practical Example

We shall use a typical PNP medium-frequency junction germanium transistor as a practical example. Furthermore we shall find the relation between conversion ability and the application conditions of the transistor and between oscillatory property and the input frequency.

From the transistor static curve of Figure 3, we can obtain the relation between transconductance and bias voltage (Figure 4). From the two curves of Figure 4 one sees that when the bias voltages are equal, the transconductance at V_c = -6 volts is higher than that at V_c = -3 volts. Therefore we select V_c = -6 volts as the collector voltage. Figure 3 shows a small group of low-frequency parameters measured at V_c = -6 volts and I_e = 1 ma. With the above information, one can begin the analysis of the conversion ability of the transistor converter.

The bias of the transistor changes with the oscillatory signal

$$V_{BE} = u + V_o \cos w_o t. \qquad (1)$$

The bias changes between two extreme values (V_1 and V_7)

$$V_7 = M + V_o \qquad V_1 = M - V_o$$

The transconductance of the transistor also changes between two values, the largest value g_7 and the smallest value g_1 (see Figure 5). If we control the oscillatory condition of the converter and at the same time change the amplitude V_o of oscillatory signal and the bias u such that the maximum bias V_7 is fixed ($M + V_o$ is a constant), then the largest value of transconductance g_7 of this converter is a constant. We shall study this kind of a converter; pick V_7 = -0.19 V. and change M, Vo such that $M + V_o$ = -0.19 V.

With the above method we obtained the relation between g_{c1} $\bar{C}_{b'e}$ and the oscillatory property. (Figure 7) We also found the relation between "effective conversion transconductance" and oscillatory property at input frequences of 1, 1.5 and 2 megacyles. (Figure 8) From Figure 7 one sees that when bias (m) increases (amplitude (Vo) decreases), g_{c1} increases also. From Figure 8 one sees that the "effective conversion transconductance" and the ability of conversion are at maximum when u lies between -0.11 and -0 13 volt. Hence Figure 8 can be used to determine the conditions for the oscillator.

One also sees the relation between conversion ability and input frequency. For the use of a radio receiver, the converter cannot be dependent on the input frequency. The ability of conversion cannot change as the frequency changes. Figure 9 shows the relation between the conversion ability and the input frequence [We use the ratio $\left(\frac{g_{\xi 1}(fs)}{g_{\xi 1}(1)}\right)$, where $g_{\xi 1}$ (fs) and $G_{\xi 1}$ (1) are the effective conversion transconductance at input frequences fs and 1 mc. respectively].

From Figure 9 one can see that when the bias (m) is small, the effect of change of input frequency on the conversion ability is small.

The best conditions for the oscillator of the converter should be determined by the largest conversion ability (largest $g_{\xi 1}$) and the smallest dependence on the input frequency $\left[\frac{g_{\xi 1}(f_2) - g_{\xi 1}(f_1)}{f_2 - f_1}, f_1 \text{ and } f_2 \text{ represents 2 different input frequencies} \right]$. The above two conditions are determined by the property of the oscillator. However one cannot change the property of the oscillator to simultaneously meet these two conditions. Hence in practical cases, one must pick the property of the oscillator to meet the actual requirements.

6. Conclusions

This article introduces "effective conversion transconductance" to represent the conversion ability of transistor converters, and uses it for selecting transistor converters. A method to analyze "effective conversion trrnsconductance" is established, and the relation between conversion and oscillatory properties is calculated. A practical example is used to show the methods of calculations of various properties. In the practical example, we use a medium-frequency PNP transistor. Because of the limitation of the frequency response of the selected transistor, during operation the conversion ability changes as the frequency of the input signal changes. If one uses transistors with more superior frequency response in the converter, this defect can be improved.

FIGURE APPENDIX

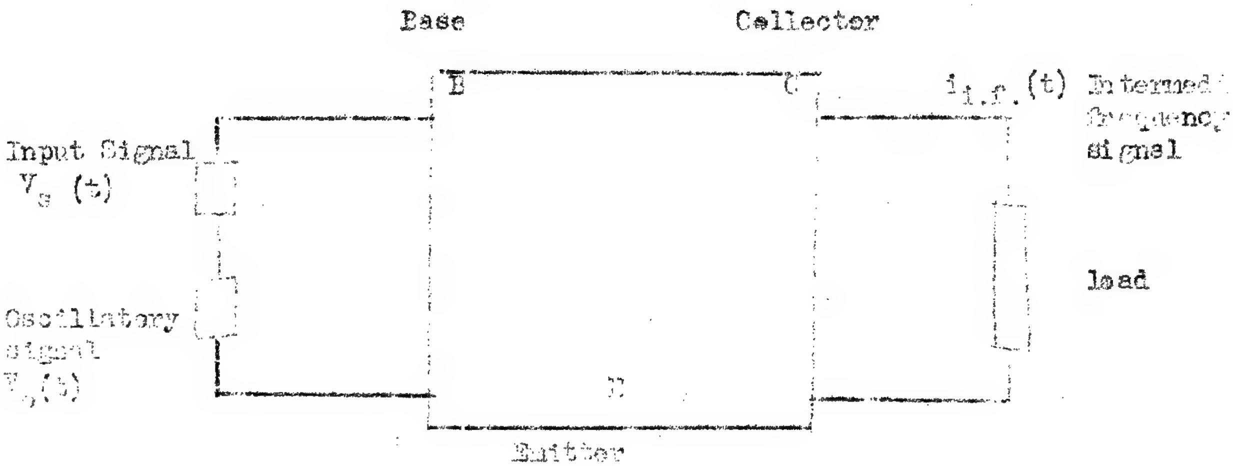


Figure 1. Block Diagram of Common-Emitter Transistor Converter

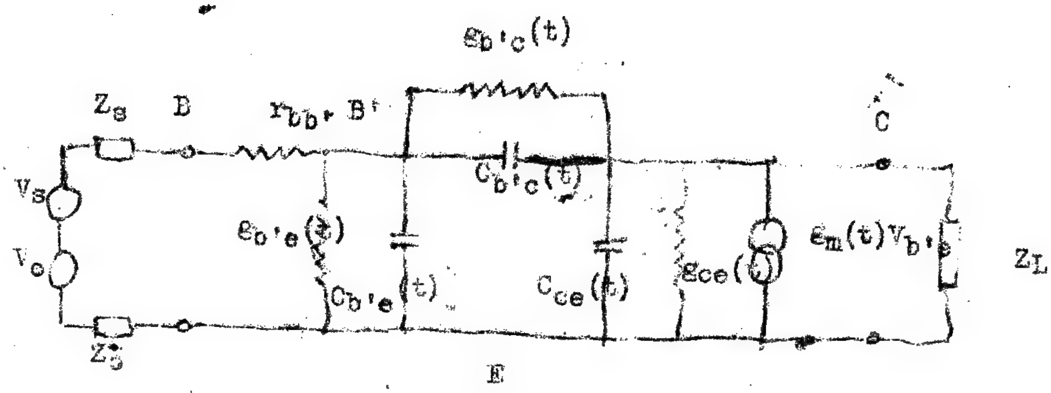


Figure 2. The equivalent circuit of the converter represented by parameters

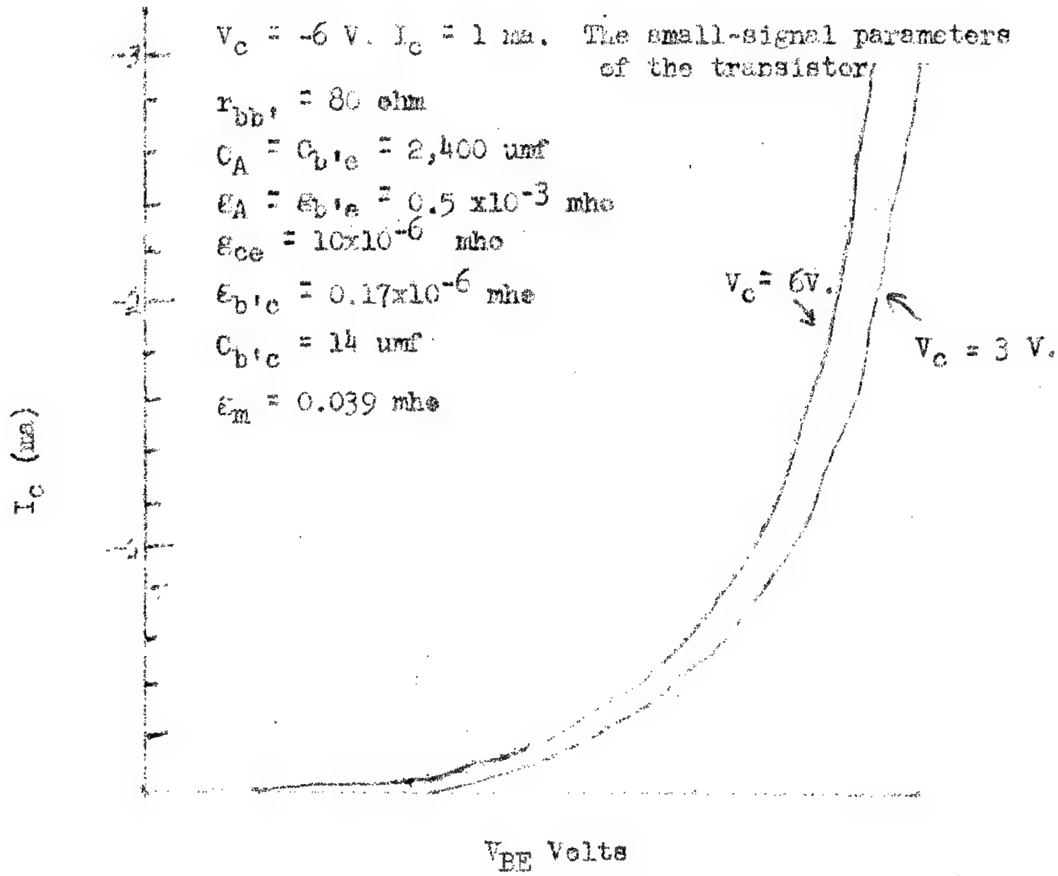


Figure 3. Static Curve of a typical PNP Transistor

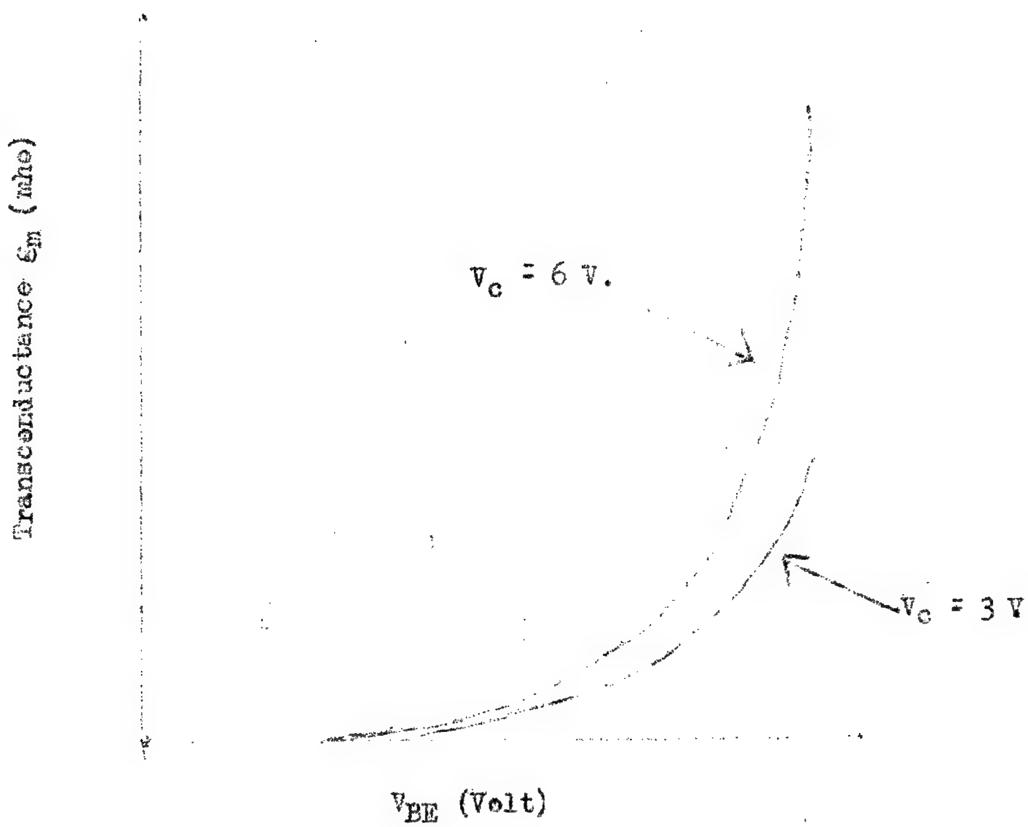
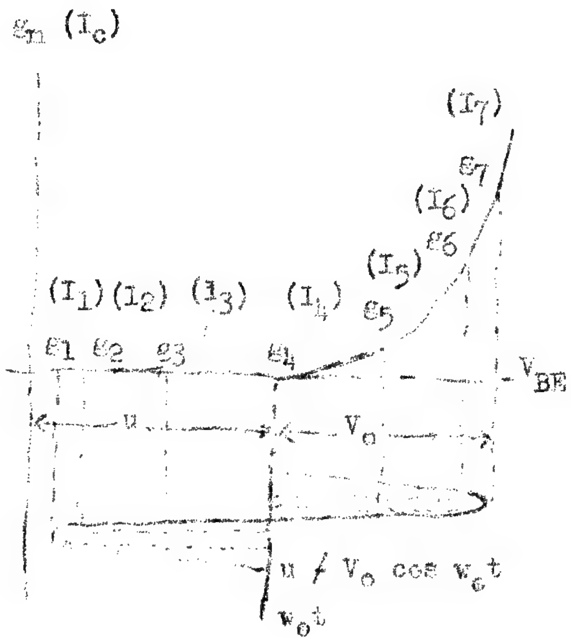


Figure 4. Transconductance vs. Bias Voltage for PNP Transistor



$w_o t$	e_m	I_c
0	e_7	I_7
30°	e_6	I_6
60°	e_5	I_5
90°	e_4	I_4
120°	e_3	I_3
150°	e_2	I_2
180°	e_1	I_1

Figure 5. Graphic Determination of e_{c1} and I_c

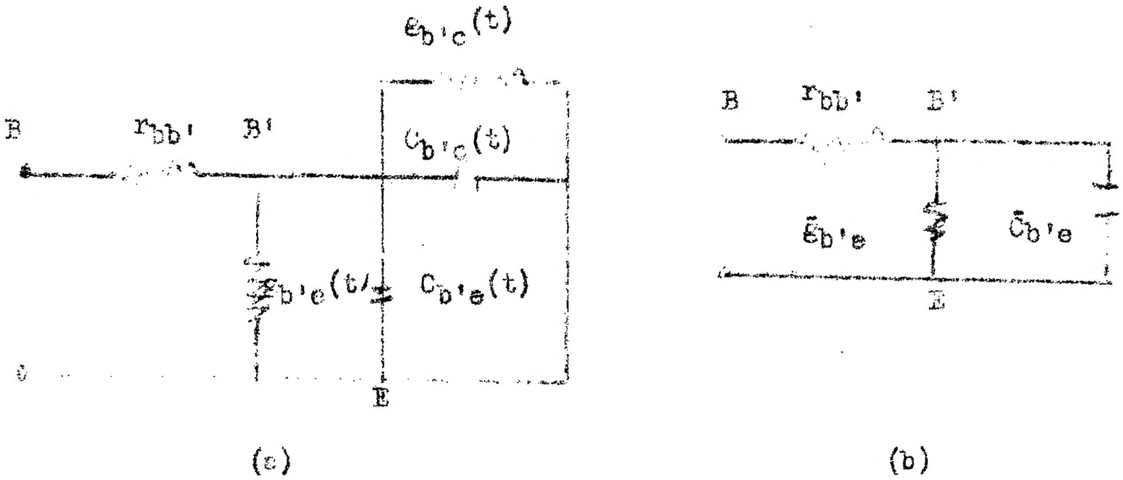


Figure 6. The Input Impedance of the Converter (a) and its Simplified Diagram (b)

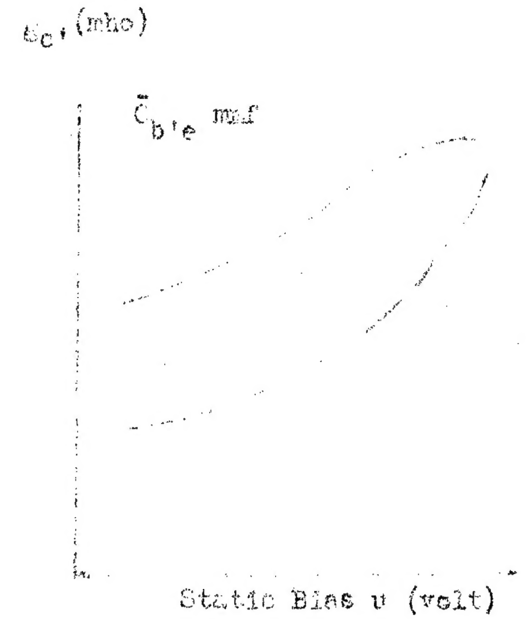


Figure 7. Oscillatory Property vs. g_{c1} and $\bar{C}_{b'e}$

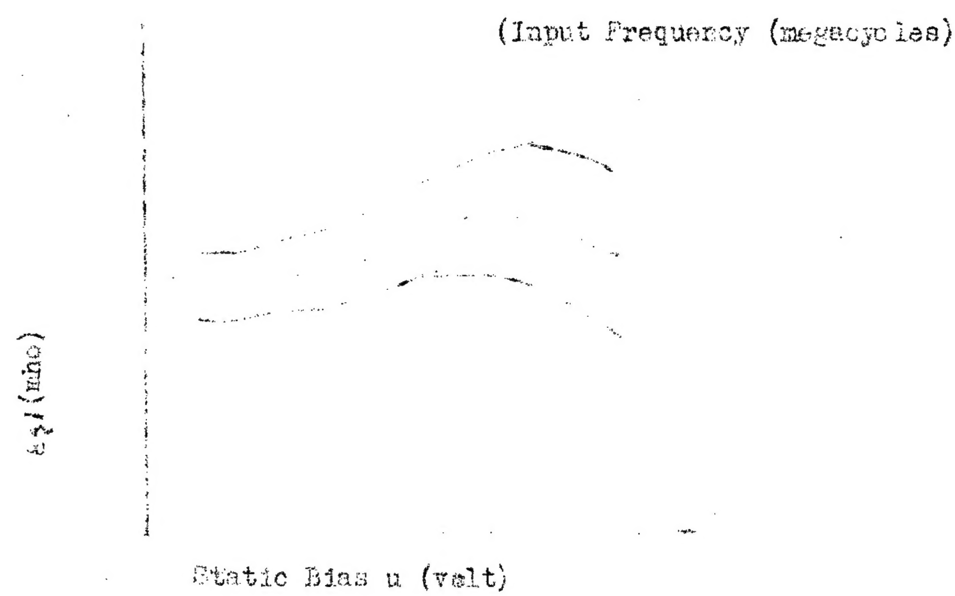


Figure 8. Oscillatory Property vs. $g_{\xi 1}$

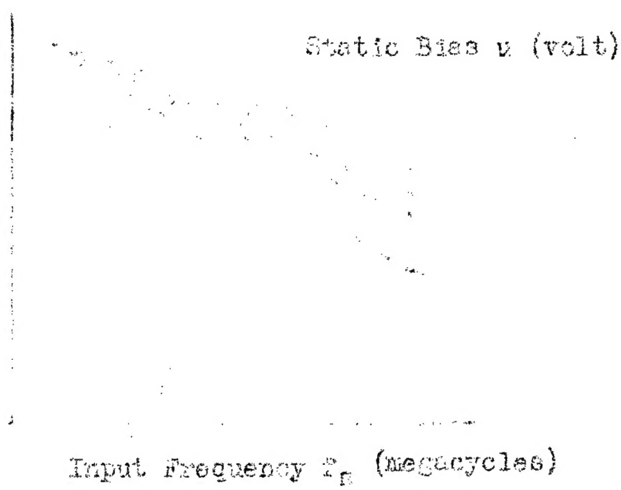


Figure 9. Conversion Ability vs. Input Frequency

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